TEST/MODEL CORRELATION FOR MARS PATHFINDER MULTI-BODY SYSTEM DROP TESTS

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ABSTRACT

A multi-body dynamics computer model was used extensively for the Mars Pathfinder mission to simulate its innovative and unconventional atmospheric entry, descent and landing approach. To verify the accuracy and validity of this model which was vital to the success of this mission, two multi-body system drop tests were performed and augmented by an extensive model correlation effort. The end product is a test verified model that will be used in the final Mars Pathfinder terminal descent simulation.

1. INTRODUCTION

Mars Pathfinder is a $150 million unmanned Mars exploration mission designed by the Jet Propulsion Laboratory to deliver a lander, camera and instrument-laden rover to the Martian surface on July 4, 1997. The spacecraft is scheduled to launch from Cape Canaveral in December 1996.

To meet the mission requirements [1], a sophisticated and unconventional atmospheric Entry, Descent and Landing (EDL) approach has been developed. After the spacecraft enters the Mars atmosphere, a parachute will be deployed to slow descent, and the heatshield will be jettisoned when it is no longer needed. As the rest of the spacecraft parachutes down, the lander wilt be lowered by a 20-meter bridle from the backshell and the rocket's braking system will engage. The bridle will then be cut, releasing the lander surrounded with inflated airbags for a soft landing on the Martian surface.

In order to prove the EDL concept and to predict the system performance, an end-to-end multi-body dynamic simulation of the entire EDL sequence has been performed using the ADAMS program [2,3]. Since the Mars Pathfinder EDL simulation is essential to the mission success, the dynamic model used in the simulation was verified by model correlation using the data from two multi-body system drop tests:

- EDL System Drop Test;
- Lander Separation Drop Test.

2. EDL SYSTEM DROP TEST

The EDL System Drop Test was performed over a two week period, from September 28 through October 12, 1995, in Boise, Idaho. The objective was to provide experimental data to verify the dynamic model of the Mars Pathfinder EDL system in its terminal descent configuration.

2.1 Test Configuration

The test article consisted of a parachute, backshell and lander, Figure 1. The parachute was constructed in flight configuration with a fabric having a permeability coefficient scaled to the Martian atmosphere. As required by the test instrumentation, the parachute canister had non-flight dimensions. The backshell and lander were in full-scale dimensions to simulate their flight aerodynamics. The mass of the backshell and lander was based on the 3/8th scaled Mars mass. The 20-meter long lander bridle was the same as flight. The lander bridle Descent Rate Limiter (DRL) was a development test unit assembled by JPL.

2.2 Test Measurement

To provide useful data for the subsequent model correlation, the following system response was measured:

- Angular positions (x,y) of backshell and lander;
- Angular rates (z) of backshell and lander;
- Accelerations (x,y,z) of backshell and lander;
- Downward dynamic pressure on lander;

In addition, videos were taken from ground and backshell.

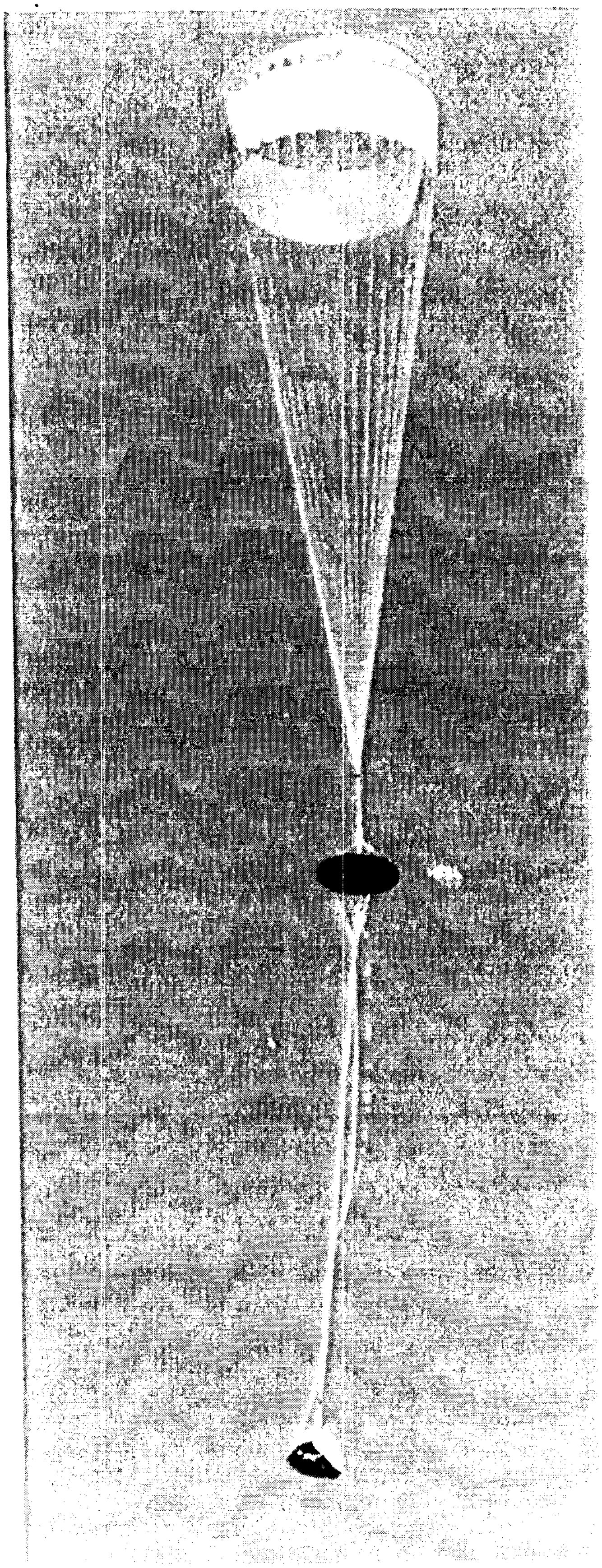

Figure 1. EDL System Drop Test

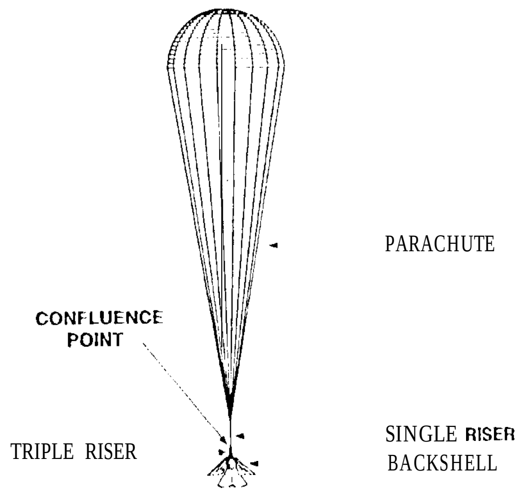

Figure 2a. TAM of EDL System Drop Test
(Before Lander Separation)

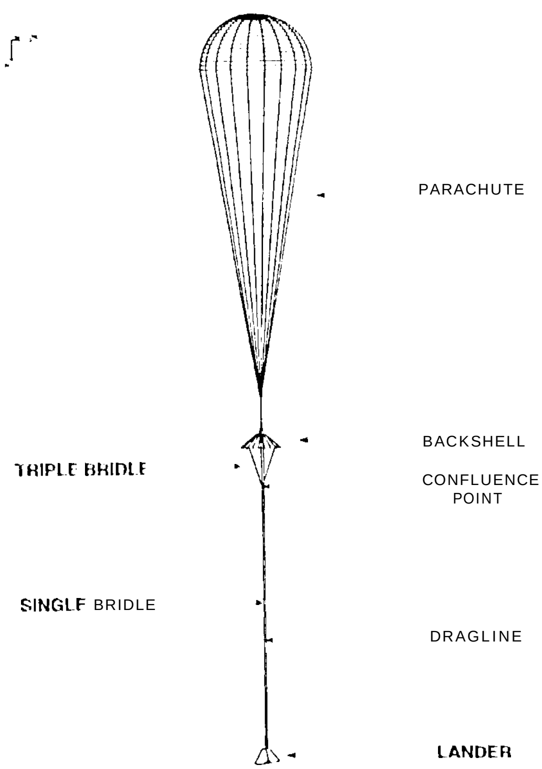

Figure 2b. TAM of EDL System Drop Test
(After Lander Separation)

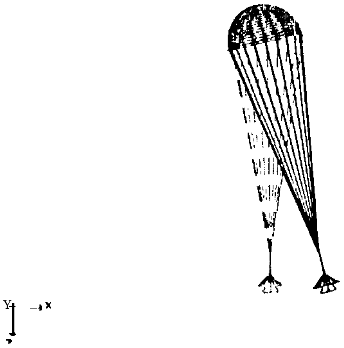

Figure 3a. Two-Body Pendulum Mode
(Before Lander Separation)

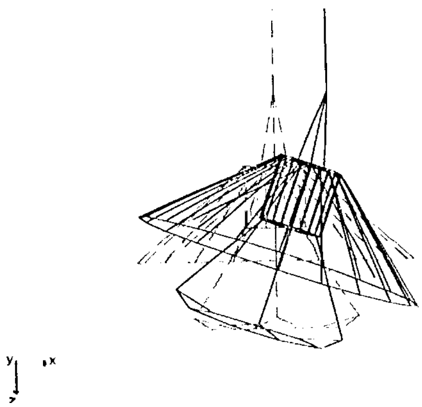

Figure 3b. Entry Body Rotational Mock
(Before Lander Separation)

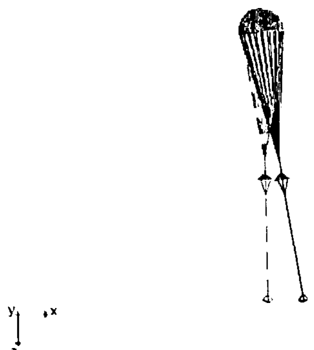

Figure 3c Three-Body Pendulum Mode
(After Lander Separation)

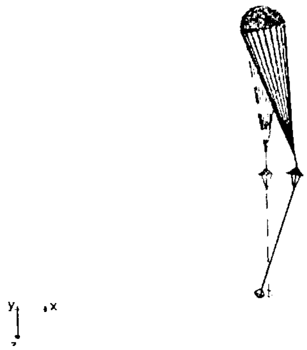

Figure 3d. Three-Body Elbow Mode
(After Lander Separation)

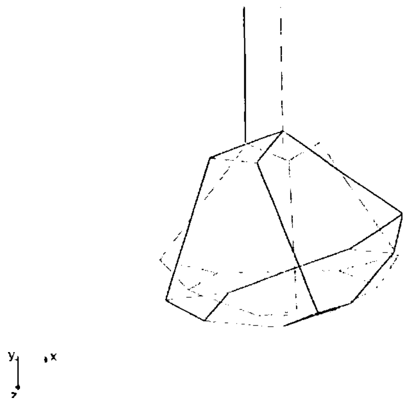

Figure 3e. Lander Wrist Mode
(After Lander Separation)

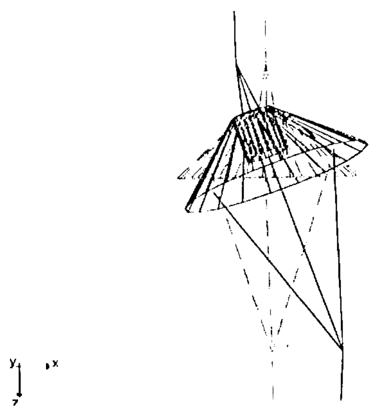

Figure 3f. Backshell Rotational Mode
(After Lander Separation)

2.3 Post Processing of Test Data

Since only the system response under 10 Hz was of interest and the fact that the test data was sampled at a very high rate of 1 KHz, the test data was reduced and processed in four steps:

- Applied a low-pass filter (0-10 Hz) to the raw data;
- Removed the pre- and post-events, and then sampled the actual event at a rate of 20 Hz. (This reduced the quantity of data by 99%.);
- Applied a Hanning window to the filtered narrow-band data;
- Performed spectral analyses on the windowed data using the Fast Fourier Transform (FFT) technique.

During the data reduction, it was observed that all the angular data was unusable due to the gyros being severely damaged by ground impact. As a result, the angular information had to be recovered from the video recording.

Note that there were two video cameras mounted on the backshell. One recorded an upward view from the backshell to the parachute; the other a downward view from the backshell to the lander. By digitizing the videos, two view angles were obtained, one up-looking and one down-looking.

2.4 Test Analytical Model

As shown in Figures 2a and 2b, a three dimensional multi-body dynamic model of the test configuration was developed for the model correlation. This Test Analytical Model, or TAM, consisted of a disk gap-band parachute, backshell, bridle and lander. The TAM was a modified version of the dynamic model used in the Mars Pathfinder EDL simulation [2].

2.5 Analysis Modal Properties

The analysis modal properties (natural frequencies, damping and mode shapes) were predicted by linearizing the TAM in two test configurations [4]: (1) two-body configuration before the lander separation, Figure 2a; (2) three-body configuration after the lander separation, Figure 2b.

The mode shapes predicted by the TAM are shown in Figures 3a to 3f. Due to symmetry, the system modes are in pairs and only one of each pair is shown. The other is similar in shape, but orthogonal.

2.6 Test Modal Properties

FFT spectra of the acceleration data were used to extract the test modal properties, mainly the natural frequencies and damping. The mode shapes were estimated from the videos. A typical acceleration time history and the corresponding FFT spectrum are illustrated in Figure 4.

Note that the FFT spectra of different time segments were examined to identify the system modal properties for the two test configurations mentioned above: (1) 15-20 sec time segment was used for the two-body configuration; (2) 40-110 sec time segment was used for the three-body configuration. The test modal properties are listed in Table 1.

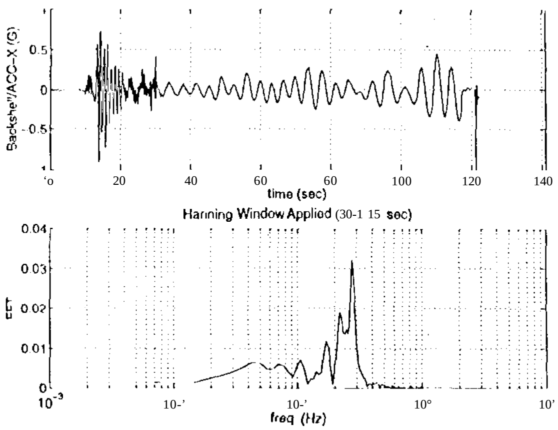

Figure 4 Typical Acceleration and FFT Spectrum

2.7 Model Correlation

Mass Properties Update

The first step of the model correlation process was to thoroughly review and update the mass properties. The mass properties of each modeled body in the TAM were updated based upon either the actual measured weight or the estimates from the CAD model.

Since the frequencies of the local lander and backshell modes are sensitive to their own c.g. z-coordinates. The z-coordinate of the lander c.g. was refined by matching the frequency of the lander wrist mode, Figure 3e. After the adjustment of the lander c.g., the backshell c.g. z-coordinate was updated by correlating the frequency of the entry body rotational mode, Figure 3b.

Damping Coefficients Adjustment

'1'0 reflect the high damping observed from the test data, the damping of the lander wrist mode in the TAM was increased to5% by adding a rotational damper.

As described in section 3, the DRL drag coefficient was adjusted from the pre-test value of 0.0055 to 0.0073 based cm the measured lander deployment time. This shows that the I)RL introduced more damping during the test than that predicted by the pre-test TAM. As a resul 1, there was very lithe lander oscillation observed at the end of the lander deployment.

It was also observed that the actual bridle damping was higher than that assumed in the pre-test TAM. Based on the amplitude of snatch acceleration at the end of lander deployment, the bridle damping was increased to 10,000 kg/sec.

Aerodynamic Model Correlation

The critical parameter for parachute stability is the aerodynamic coefficient of C_N vs. angle of attack which determines the normal component of aerodynamic force acting on the parachute. The primary El)1. system drop test data available for verifying the parachute C_N are the up-looking and down-looking view angles. Since the view angles were strongly dependent on the backshell aerodynamic stability, the parachute aerodynamic coefficient C_N was correlated after the backshell wind tunnel testing.

in this study, the parachute C_N was parametrized as: $C_N(\alpha) = C_1 \sin(\alpha) + C_2 \sin^2(\alpha)$, where α is the angle of attack, and C_1 and C_2 are two constant coefficients. With the backshell aerodynamic properties known from wind tunnel test, a total of 336 EDL simulation runs were made with possible ranges of C_1 and C_2. 'l'he results are plotted in Figures 5a and 5b.

It was observed that the up-looking view angle varied between 2 to 6 deg, and the down-looking view angle between 1 to ?.5 deg. To reproduce the view angle ranges observed, the combinations of C_1 and C_2 had to be selected between the contour lines of 2 and 6 deg (Figure 5a) and those of 1 and 2.5 deg (Figure 5b). The selected (C_1,C_2) set was used to define the correlated parachute aerodynamic model for the final Mars Pathfinder EDL simulation.

Table 1. Summary of Model Correlation Results for Mars Pathfinder EDL System Drop Test

	7	I	Ti :f	
Description of Mode Shapes	Freq. (Hz)	Damping (%)	Freq. (Hz)	Damping (%)
2-Body Pendulum Modes (Before Lander Separation)	01019 0.1019	14.5 145	n/a (rec. too short	n/a (rec too short)
Entry Body Rotational Modes (Before Lander Separation)	08951 0.9118	55 5.5	0.907s o 9288	~7 -7
3-Body Pendulum Modes (After Lander Separation)	00788 0.0789	124 11,8	o 0779 0.0780	-lo -lo
3-Body Elbow Modes (After Lander Separation)	02754 0.2355	0.01 0.2-3	0.2269 0269-1	-1 -1
Lander Wrist Modes (After Lander Separation)	0.9891 1.0113	5,2 5.3	0.9429 0.9502	~4 ~4
Backshell Rotational Modes (After Lander Separation)	1.8847 19711	20 2.0	n/a (damped)	n/a (damped)

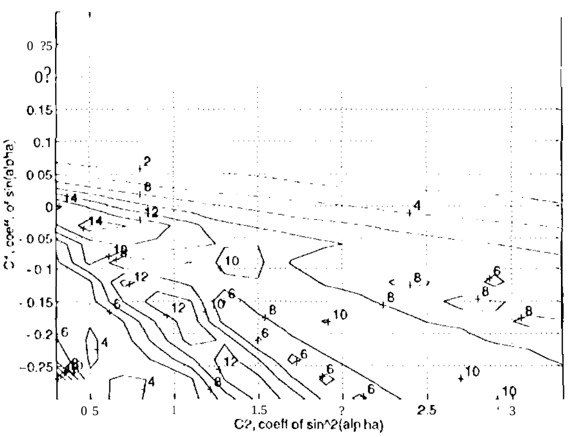

Figure 5a. (C_1,C_2) vs. Up-Looking View Angle

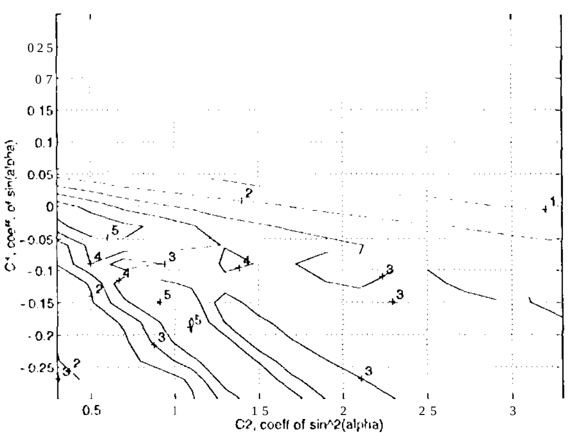

Figure 5b. (C_1,C_2) vs. Down-Looking View Angle

2.8 TAM Predictions vs. Test Results

The results are summarized in Table 1 by comparing the modal properties predicted by the correlated TAM and those identified from the test data. in general very good agreement between the analysis and test modal properties, especially the frequency correlation, was achieved

3. LANDER SEPARATION DROP TEST

The Lander Separation Drop Test was performed at the Missile Engagement Simulation Arena of China Lake Naval Weapons Center, California in September and October, 1995. The objectives were to verify that the mechanical devices for the lander separation would function in their flight configu ration as well as to provide the test data to validate the dynamic model used in the Mars Pathfinder EDL simulation.

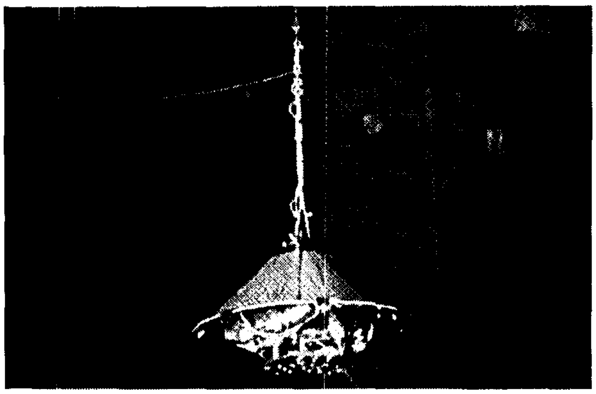

Figure 6. Set -up for Lander Separation Drop Test

3.1 Test Configuration

The test set-up is shown in Figure 6. Prior to separation the lander was attached to the backshell interface plate. A drag line was employed to reduce the snatch force on the lander at the end of deployment. This dragline line was stored inside a Descent Rate limiter (DRL) in the form ofa payout reallocated inside the lander and connected toa point ton the backshell at the other end. The lander was also connected to three points on the backshell by a bridle system comprising a single bridle and a triple bridle.

The lander/backshell assembly was attached to a crane hook with three flexible parachute-like bridles. The cram hook was suspended on a single cable to the ceiling of the building.

An analytical animation of the drop test is shown in Figure 7, where the coordinate system is also defined.

Two similar tests were conducted. Only the first will be described here. in this test, the backshell/lander assembly was initially suspended vertically so that prim to separation, all initial velocities were zero.

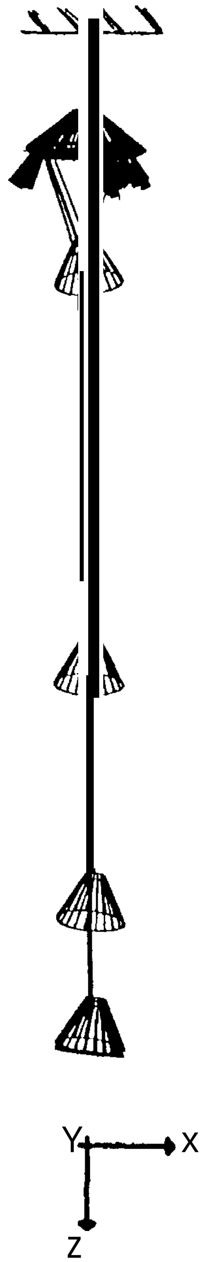

Figure 7. Animation of Lander Separation Drop Test

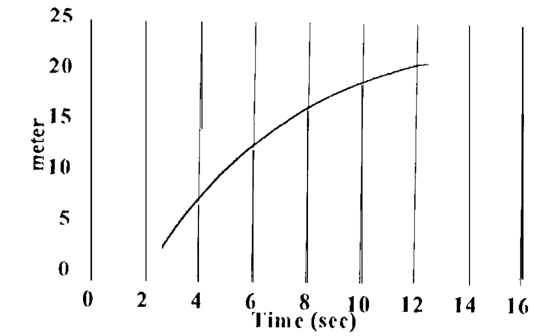

Figure 8a. Lander e.g. Vertical Disp. vs. Time (Test)

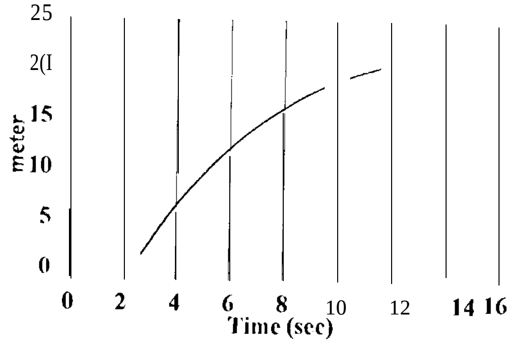

Figure 8b. Lander c.g. Vertical Disp. vs. Time (TAM)

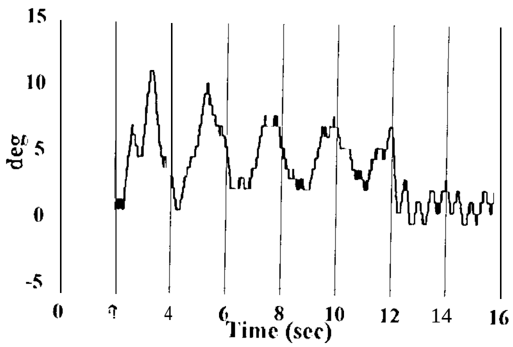

Figure 9a. Backshell Rotation about X Axis (Test)

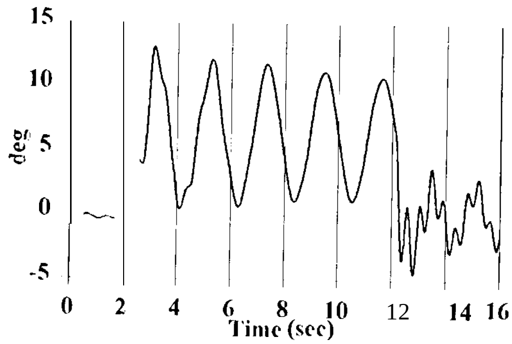

Figure 9b. Backshell Rotation about X Axis (TAM)

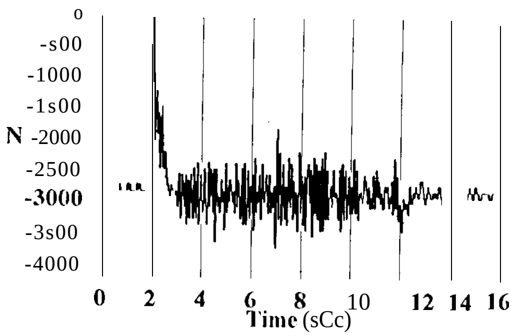

Figure 10a. Force in Single Riser (Test)

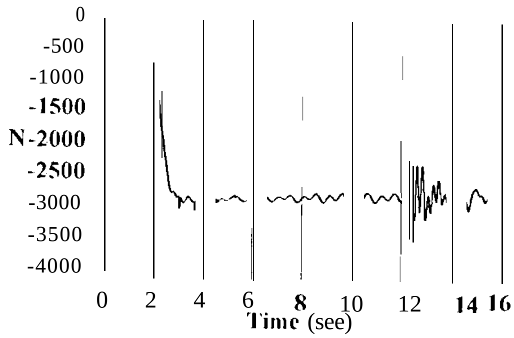

Figure 10b. Force in Single Riser (TAM)

3.2 Test Measurement

A string potentiometer, load cells, gyros and accelerometers were used to measure the following system response during the t,st

- Separation distance;
- Bridle and reaction forces;
- Translation/rotational motions and accelerations of the backshell and lander;

3.3 Test Analytical Model

A test analytical model (l'AM), Figure 7, was modified from the dynamic model used in the Mars Pathfinder EDL simulation, as described in section 2.4. All aerodynamic forces were removed since testing was conducted indoors. Ground boundary condition was imposed above the backshell at the ceiling. Gravity was changed to 9.806 m/sec^2 to reflect Earth condition.

3.4 Model Correlation

Mass Properties Update

Mass properties were adjusted to match measured values. These values for the backshell and lander were 104.31 kg and 175.61kg respectively.

Damping Coefficients Adjustment

Based on the measured lander deployment time, the drag coefficient of DRL was adjusted to a value of 0.008.

To match the amplitude of vertical oscillation at the end of lander deployment, the bridle damping was adjusted to a value of 8000 kg/see.

3.5 TAM Predictions vs. Test Results

Figures 8a and 8b show respectively the vertical displacement of the lander e.g. vs. time from test and TAM. The excellent agreement in the deployment time was obtained by adjusting the DRL drag coefficient.

"l'he backshell rotation about the X axis from test and TAM is shown in Figures 9a and 9b respectively. Very good frequency correlation is obtained for the duration, from 2 to 12 see, of the lander deployment. The amplitude correlation is initially quite good even though the test data indicated higher damping during the later stages of deployment.

The force in the single riser (cable connecting the backshell to ceiling) from test and TAM is shown in Figures **10a and 10b** respectively. The TAM predicted the initial force quite accurately although the snatch force at the end of deployment was over-predicted. The reason is that the actual damping mechanism included the breaking of stitches connecting the bridle to the lander petal and was more complex than the viscous model assumed in the TAM.

4. CONCLUSIONS

The dynamic model used in the Mars Pathfinder EDL simulation was successfully validated as described in sec[ions 2 and 3. The test verified model will be used to develop a dynamic model for the final end-to-end Mars Pathfinder EDL simulation. The simulation results will be reviewed to assess the Mars Pathfinder EDL system performance.

5. ACKNOWLEDGMENT

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